

EXAMINATION OF THE STRUCTURAL RESPONSE OF THE ORION EUROPEAN SERVICE MODULE TO REVERBERANT AND DIRECT FIELD ACOUSTIC TESTING

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The NASA Orion Multi-Purpose Crew Vehicle (MPCV), comprised of the Service Module, the Crew Module, and the Launch Abort System, is the next generation human spacecraft designed and built for deep space exploration. Orion will launch on NASA's new heavy-lift rocket, the Space Launch System. The European Space Agency (ESA) is responsible for providing the propulsion sub-assembly of the Service Module to NASA, called the European Service Module (ESM). The ESM is being designed and built by Airbus Safran Launchers for ESA.

Traditionally, NASA has utilized reverberant acoustic testing for qualification of spaceflight hardware. The ESM Structural Test Article (E-STA) was tested at the NASA Plum Brook Station's (PBS) Reverberant Acoustic Test Facility in April-May 2016.

However, Orion is evaluating an alternative acoustic test method, using direct field acoustic excitation, for the MPCV's Service Module and Crew Module. Lockheed Martin is responsible for the Orion proof-of-concept direct field acoustic test program. The E-STA was exposed to direct field acoustic testing at NASA PBS in February 2017.

This paper compares the dynamic response of the E-STA structure and its components to both the reverberant and direct field acoustic test excitations. Advantages and disadvantages of direct field acoustic test excitation method are discussed.

Keywords: direct field acoustic testing, reverberant acoustic testing, spacecraft acoustic testing, vibroacoustics

1. Introduction

The NASA Orion Multi-Purpose Crew Vehicle (MPCV), comprised of the Service Module, the Crew Module, and the Launch Abort System, is the next generation human spacecraft designed and built for deep space exploration. The Service Module is made up of the Crew Module Adapter (CMA) and Spacecraft Adapter Jettison (SAJ) Fairings, which are supplied by Lockheed Martin, and the European Service Module (ESM), designed and built by Airbus Safran Launchers for the European Space Agency. Figure 1 illustrates the Orion MPCV spacecraft and its components.

The Orion MPCV will launch on NASA's new heavy-lift rocket, the Space Launch System. The Exploration Mission-1 (EM-1) is an un-crewed mission of the Space Launch System/Orion MPCV with a mission timeline of about seven days to go beyond the moon and back to the earth in 2018.

In order to qualify the ESM for flight, a comprehensive test campaign [1] was conducted at NASA's Plum Brook Station (PBS) in Sandusky, Ohio using dedicated qualification test hardware, the European Service Module Structural Test Article (E-STA). The test campaign included acoustic, sine vibration, and shock environmental testing, as well as solar array deployment testing.

Reverberant acoustic testing was performed in April-May 2016 on the E-STA to achieve several test objectives: verifying structural capability under acoustic loading, validating dynamic models, validating ESM's components random vibration test specifications, and qualifying the Solar Array Wing (SAW). The SAW is a large, lightweight panel, which couples well to the acoustic field.

The E-STA also was exposed to direct field acoustic testing (DFAT) in February 2017 to demonstrate an alternative test approach for efficient testing of Orion MPCV flight production modules. The DFAT test objectives included achieving the protoqual acoustic excitation levels and predicted ESM flight response, as well as demonstrating the capability to response limit.

The objective of this paper is to compare the structural vibration response of the E-STA using similar acoustic test levels but with different types of acoustic excitation (reverberant and direct field). Over 700 instrumentation channels (microphones, accelerometers, and strain gauges) were measured in each test program. Emphasis during both acoustic test programs was the critical structural response of the SAW.

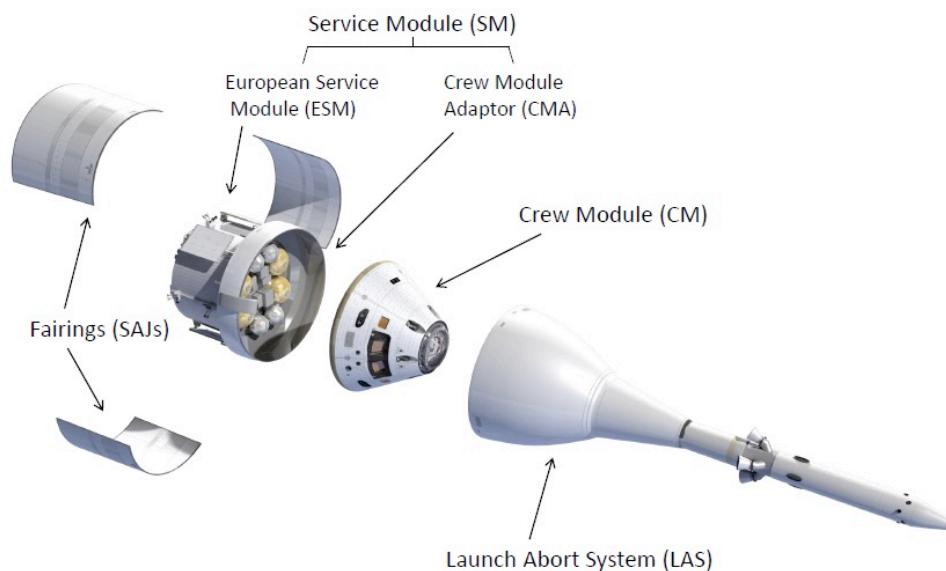


Figure 1: Orion Multi-Purpose Crew Vehicle

2. Spaceflight Hardware Acoustic Testing

Reverberant acoustic testing is the traditional test method used for well over 40 years to qualify spaceflight hardware. In a reverberant acoustic test, an approximately diffuse acoustic field is produced by a dedicated test facility with hard reflective walls and an acoustic noise generation system comprised of individually controlled horn/modulators. Test control is maintained using a one-third-octave band control system.

Orion is evaluating an alternative acoustic test approach using DFAT at the module level. DFAT uses a portable acoustic test setup of commercial speaker stacks that are assembled to surround the test article. The Multiple-Input Multiple-Output (MIMO) acoustic control strategy controls each speaker stack via separate, independent drive signals with feedback from multiple, independent control microphones.

3. Reverberant Acoustic Testing

The Reverberant Acoustic Test Facility (RATF) [2] at NASA PBS is a reverberant test facility capable of achieving an empty chamber overall sound pressure level (OASPL) of 163 dB using a combination of 36 horn/modulators grouped at seven different horn cut-off frequencies (25 Hz, 35 Hz, 50 Hz, 80 Hz, 100 Hz, 160 Hz, and 250 Hz). The combination of the RATF size (2,860 m³) and acoustic power is unprecedented amongst the world's known active reverberant acoustic test facilities.

The E-STA was tested at RATF in April-May 2016 [3]. Ten reverberant tests were performed at various sound pressure levels and two propellant tank fill conditions (empty, filled). Figure 2a illustrates the E-STA test article as configured for reverberant acoustic testing in the RATF. Figure 2b identifies the pertinent test article components: SAW, Service Module (SM) Outer Cavity, and SAJ Fairings. The E-STA was excited to external qualification levels as high as 149.4 dB OASPL for test durations as long as 180 seconds. Modifying the RATF-generated external noise to achieve the target sound pressure levels in the SM Outer Cavity (acoustic cavity behind the SAJ Fairings) was critical in achieving the test objectives of exciting the E-STA components correctly, especially for the SAW Qualification Model (QM). The acoustic field in low frequency ($f < 50$ Hz) was difficult to reach due to inherent room modes of the reverberant chamber and the constraints on the shape of the targeted spectrum. Otherwise, all the test objectives were successfully met.

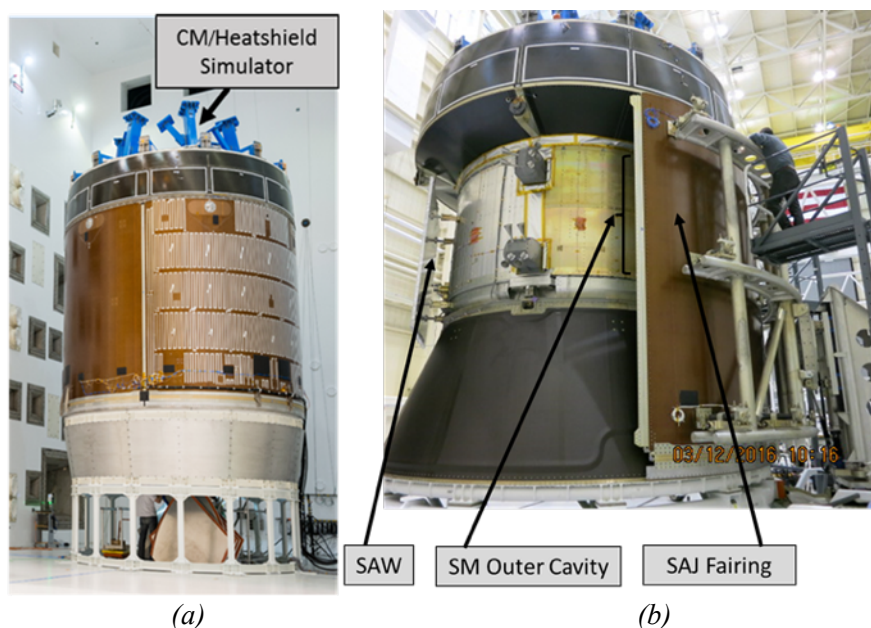


Figure 2: E-STA Reverberant Acoustic Test Configuration

4. Direct Field Acoustic Testing

The E-STA was exposed to DFAT excitation at NASA PBS in February 2017. Lockheed Martin is responsible for the Orion proof-of-concept DFAT program and contracted with MSI DFAT Services, LLC to conduct the test. Figure 3 illustrates the E-STA test article as configured in the DFAT. The SAW QM is highlighted in Figure 3a, and the fully assembled speaker stack configuration is shown in Figure 3b. Test configuration differences from the Reverberant acoustic test include the absence of both the SAJ Fairings and the Crew Module/Heatshield mass simulators in the DFAT. Due to the current DFAT external excitation limitations (maximum achievable sound pressure level ≤ 147 dB OASPL), the SAJ Fairings were removed for the DFAT configuration to enable test control at targeted SM Outer Cavity test levels. The Crew Module/Heatshield Simulator was removed from the DFAT configuration based on Lockheed Martin's pre-test analysis that indicated the critical E-STA structural responses were still similar to that of the Reverberant test configuration. The SAW QM structural vibration was response limited during the DFAT to protect it from exceeding its component qualification levels that were established in the E-STA Reverberant test.

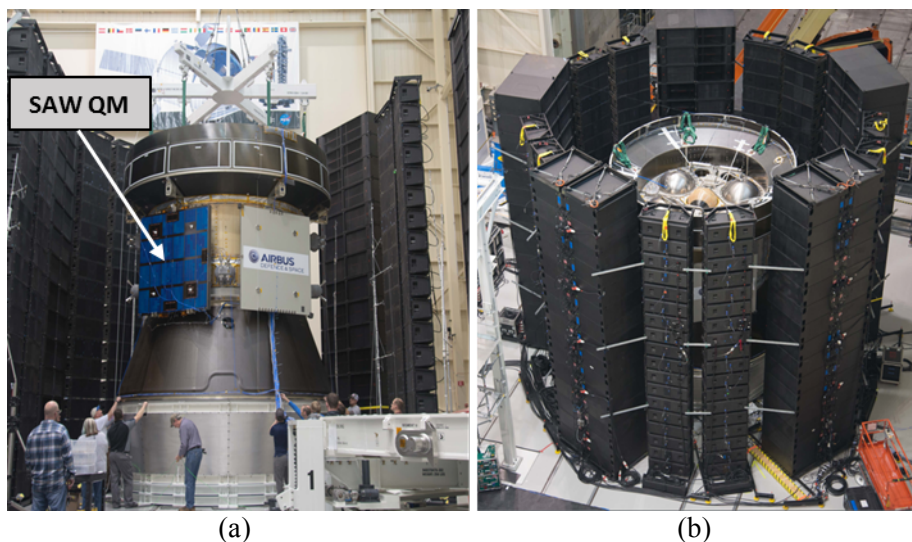


Figure 3: E-STA Direct Field Acoustic Test Configuration

A total of seven DFAT tests were successfully completed on the E-STA, all with an empty propellant tank configuration. The highest DFAT test level was 143.8 dB OASPL.

The DFAT system provided by MSI consisted of ten speaker stacks each with fifteen sub-woofer boxes, and ten speaker stacks each with eighteen 3-way boxes arranged in a cylinder around the E-STA. The inner diameter of the E-STA test volume was 8.5 m and the total height was 9.6 m. The frequency range was covered from 20 Hz to approximately 250 Hz by the sub-woofer boxes, and from 160 Hz to 10 kHz by the 3-way boxes.

Test control was provided by a MIMO acoustic closed-loop control system using fifteen independent drives that were mixed to improve spatial uniformity and then delivered to each of the speaker stacks. Audio feedback was provided by fifteen independent control microphones randomly placed within the test annulus and above the E-STA. The controller used narrow-band (3.125 Hz) spectral analysis to compute and compare with the one-third-octave reference level that was internally converted to a narrow-band reference. Narrow-band acoustic control provides all features normally available for random vibration control, including response limiting and over-test protection.

The entire DFAT system was delivered to NASA PBS in five trucks (four full-sized trailers and one half-size trailer), plus a separate trailer that contained the diesel generator system. The complete process of unloading, installing, checking out the equipment, making seven separate test runs with intermediate data review and meetings by NASA and other customer personnel, disassembling and

reloading the equipment, took only six days. The DFAT process went smoothly from end to end, and represented the 128th DFAT provided by MSI over the last 16 years, and the 3rd DFAT for the Orion MPCV program.

5. Test Results: Comparison of E-STA Structural Vibration Response

Similar sound pressure levels (136.2 dB OASPL) and spectral shape were applied in both the Reverberant and the DFAT acoustic tests of the E-STA. These respective acoustic excitation levels represented the measured SM Outer Cavity level during one of the Reverberant tests with SAJ (Qualification level - 6 dB), and the corresponding excitation level for the DFAT without SAJ. The structural response comparisons shown in this paper for these two tests focus on the SAW QM locations, as well as the flight-like Water Tank and the Orbital Maneuvering System Engine (OMS-E). Only a very limited subset of the over 700 instrumentation channels from the E-STA DFAT test has been analysed to date.

The SAW QM structural vibration was response limited during DFAT in order to protect it from exceeding its component qualification levels established during the E-STA Reverberant tests. This response limiting was implemented using the Panel 3 normal-direction accelerometer (Figure 4a, accelerometer A148Z) at the corner of the SAW QM. Response limiting protected the SAW QM from fatigue damage when testing to the full acoustic level, by reducing the in-plane micro-strain in the hold down Panel 3 location (Figure 4b, Strain Gauge SG190).

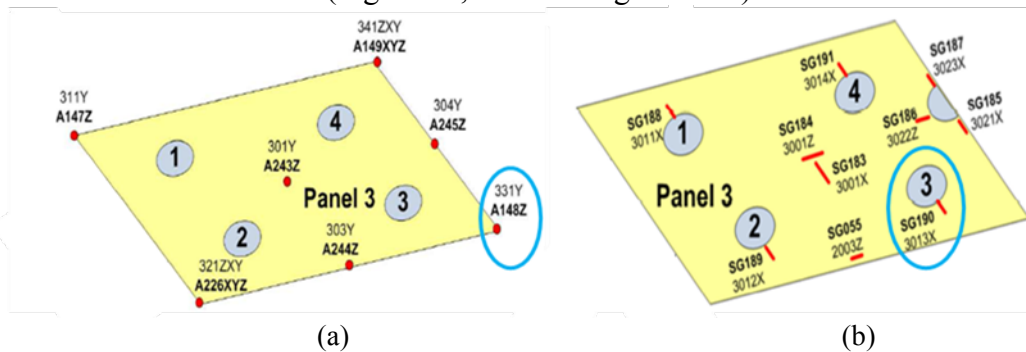


Figure 4: SAW QM Instrumentation on Panel 3

In general, the SAW QM structural responses have a similar spectral shape (Figure 5) for the two tests for both acceleration and strain. At 90 Hz, a higher response is observed in the DFAT test compared to the reverberant test. This corresponds to the DFAT excitation strongly coupling with the SAW QM's large lightweight panel structural resonance. The structural response differences noted in low frequency ($f < 40$ Hz) are in part due to structure-borne random vibration transmission from the SAJ Fairings to the ESM. This structural response is not present in the DFAT test (without the SAJ Fairings) compared to the Reverberant test (with the SAJ Fairings).

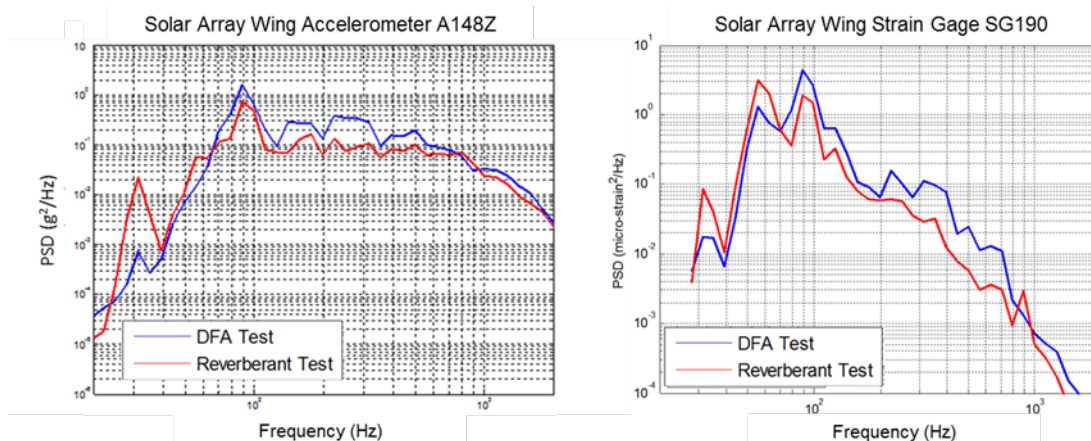


Figure 5: SAW QM Structural Responses Comparisons (Accelerometer A148Z and Strain Gauge SG190)

The structural responses for both the OMS-E interface (normal direction to the support) and the Water Tank (in-plane direction) remain within acceptable tolerances between the Reverberant and the DFAT (Figure 6). Even though the results of these comparisons are promising for this E-STA DFAT development test, further detailed analyses will have to be performed prior to the EM-1 Service Module DFAT protocol test to avoid equipment overstressing with regards to their qualification levels before the first flight.

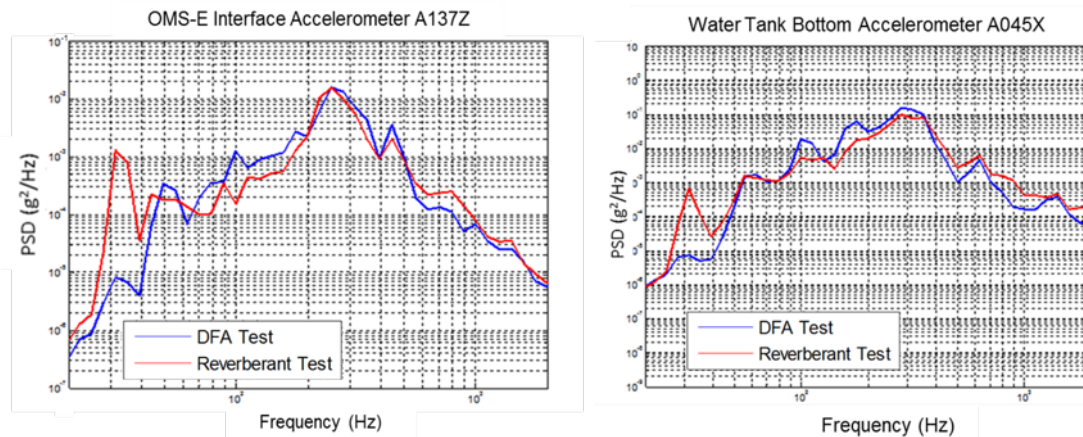


Figure 6: OMS-E Interface and Water Tank Bottom Interface Structural Responses Comparisons

6. Advantages and Disadvantages of Direct Field Acoustic Testing

DFAT has been utilized for system level acoustic testing of spaceflight hardware for over 16 years [4-7]. Through the application of the testing technology, implementation advantages and disadvantages have been identified. NASA-HDBK-7010 [8] provides technical guidance on DFAT including pre-test analysis, test planning and setup, response instrumentation, and test control.

6.1 Advantages

The main advantage of DFAT is the test facility portability, providing the convenience of assembling the test facility on-site without the transportation expense and risk to the test article. This eliminates the need for permanent infrastructure and maintenance associated with reverberant test facilities.

Direct field acoustic control is based on vibration shaker system control technology, with the ability to employ narrow-band random control and structural response limiting during testing. This is in contrast to reverberant acoustic control systems that use one-third-octave bandwidth control, and does not have the ability to structurally response limit.

6.2 Disadvantages

Historically, the main disadvantage of DFAT is spatial uniformity issues (hot and cold spots), resulting from constructive and destructive wave interference patterns and standing waves in the acoustic excitation field, with the potential of over-testing or under-testing the test article. However, recent innovations in the direct field acoustic control strategy has evolved from the early DFAT of using Single-Input Single-Output (SISO) and Multiple-Input Single-Output (MISO) to the current state-of-the-art testing utilizing MIMO acoustic control. The MIMO acoustic control strategy [9] improves spatial uniformity by creating a less coherent acoustic field.

Direct field acoustic testing is limited in the maximum achievable acoustic sound pressure level (≤ 147 dB OASPL) and continuous test duration (30 seconds) for high excitation levels. The trade-off of achievable sound level and test duration are due to the limits in the speaker acoustic power that

can be generated without overheating of the speaker cone, coils, and amplifiers. A cool down period between DFAT runs is typically required to prevent damage to the speaker and amplifier hardware.

The vibroacoustic prediction of the direct field acoustic test is an area of research and investigation [10, 11], particularly focused on improved modeling of the acoustic-structure interaction of the direct acoustic field with the test article. Promising results have been obtained using the Boundary Element Method to estimate the direct field by modeling each speaker source individually [12].

7. Conclusions

The E-STA acoustic test campaign provided a unique opportunity to compare the structural response of a complex flight-like test article to both reverberant and direct field acoustic excitations. The E-STA was tested in a reverberant chamber to its predicted qualification test levels to meet multiple test objectives to advance the qualification of the ESM hardware, and enhance design and modeling confidence. The E-STA was also exposed to DFAT to demonstrate an alternative test approach for efficient testing of Orion MPCV flight production modules. Over 700 instrumentation channels were recorded in each test.

Due to the current limitation of speaker power, the DFAT test level was unable to reach the ESM high external sound levels, as achieved in the Reverberant test to the actual launch environment. Therefore, the SAJ Fairings were removed for the DFAT testing in order to excite the E-STA to the SM Outer Cavity's acoustic levels measured in the Reverberant test (with the SAJ Fairings).

With this configuration change, similar sound pressure levels were applied in both the Reverberant and the DFAT acoustic tests of the E-STA. This allows a comparison of the structural response of the E-STA hardware for similar sound pressure levels but for two different types of excitation (reverberant and direct field). It was observed that the structural responses for the two types of excitation resulted in similar spectral shapes. The large lightweight panel structure (SAW) did couple more strongly at its panel resonant frequency in the DFAT tests. Other differences are within acceptable test tolerances or explained by test configuration differences.

Because of the SAW QM's strong coupling to the direct field acoustics, response limiting was employed to protect against excessive fatigue damage. It was observed that the SAW QM 90 Hz resonant response was greater in the DFAT test relative to the Reverberant test response. When implementing response limiting in DFAT, care should be taken to ensure other test components are not under-tested.

Neither the reverberant nor direct field test excitations exactly match the actual launch acoustic environment, which is a mixture of diffuse and propagating waves. Reverberant testing has a long history of success of qualifying aerospace hardware, whereas DFAT is experiencing increasingly widespread use in the satellite industry and has made substantial improvements in the last decade, especially relative to the usage of MIMO control to improve spatial uniformity of its acoustic field. The Orion MPCV Project will continue to assess the advantages and disadvantages of the reverberant and direct field acoustic excitation types and their effects on spaceflight hardware qualification.

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